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DEVELOPING A SUSTAINABLE ROADMAP IN KSA THROUGH THE UTILISATION OF HYDROGEN ENERGY

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ABSTRACT

The Kingdom of Saudi Arabia has been reported to have one of the highest energy consumers per capita in the world. As a result, the rapid increase in carbon dioxide emissions due to population growth has been a major challenge facing the country over the past years. Utilisation of hydrogen energy is seen as a sustainable potential to fulfil the energy needs of the country without pollution consequences. Hydrogen is known as an energy carrier that can fulfil the global energy demand due to its attractive properties, such as being storable, transportable and safe. This can normally be used as fuel in Proton Exchange Membrane fuel cell, which is an electrochemical device that converts the chemical reaction of hydrogen with oxygen to electrical energy. Production of hydrogen can be achieved through many resources, both conventional and renewable. In this paper the hydrogen production potential sources to achieve a sustainable development in the country are highlighted and the environmental and economical benefits for utilising this energy in two sectors (electricity generation and transport) are analysed.

Keywords: hydrogen energy; PEMFC; sustainability; renewable energy.

1. INTRODUCTION

The Kingdom of Saudi Arabia (KSA), the world largest crude oil exporter has announced an ambitious economic diversification plan in 2016 with the hopes of reducing the dependency on oil. This major economic diversification plan has the hopes to be carried out through implementing a number of major projects in different sectors including renewable energy, tourism, health and education. One of the main targets that were included in the plan is the addition of a new renewable energy capacity of 9.5GW by year 2023 [1]. In 2017, the KSA government have further revealed the launch of a mega-transitional city NEOM that is located in the northwest of the Kingdom, which will run 100% from renewable energy sources [2]. NEOM is hoped to be a strategic hub in the region focusing on energy, water, biotechnology, artificial intelligence and tourism. Figure 1 shows the location of the NEOM.



Figure 1: Map location of NEOM project

According to the Energy Information Administration (EIA) [3], KSA's production capacity of crude oil is around 12 million barrels per day with an estimated 16% of the world's total oil reservoirs. With such tremendous amounts of this energy resource, the economic and population growth have risen dramatically from the past decades, which have led to the increase in the consumption rate of crude oil to fulfil the energy needs inside country. Environmental pollution has also reached records high, making it among the top highest carbon dioxide emissions per capita in the world.

A lot of experts specialising in the energy sector, whether scientists or policy makers believe that hydrogen energy is a potential sustainable energy resource that could play a crucial role in satisfying the world's energy needs in the future. Hydrogen as fuel possesses substantial attractive features, such as having a high energy density and being environmentally clean and non-toxic. Moreover, this substance is abundant and can be produced either via conventional energy sources or renewable and clean energy sources.

One of the main devices that utilises hydrogen as a fuel is Proton Exchange Membrane fuel cell (PEMFC), which is used in many applications. PEMFC (shown in figure 2) is an electrochemical device that converts the reaction of hydrogen with oxygen directly to electricity, with only water and heat as by-products. A single cell in the PEMFC has less power output and hence the PEMFC usually comes in stacks where a defined number of cells are arranged in series to obtain the desired electrical power. PEMFCs have received global attention mainly due to both their high efficiency (as compared to existing combustion engines), and operating in low temperature. These devices have successfully been deployed in the portable applications (transportation) and stationary power applications for both residential and commercial.

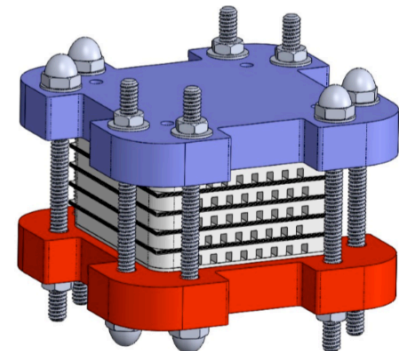


Figure 2: Illustration of PEMFC stack

The performance of the PEMFCs is described by the behaviour of the polarisation curve, which is a subject of the current density and voltage. The performance of PEMFCs has proven to be better at elevated temperature, between 60°C and 80°C due to yielding a higher reversible voltage and obtaining a reduced ohmic resistance. Moreover, different parameters can affect the behaviour of the polarisation curve, including the partial pressure of oxygen, the water contents in the reactants (humidity level), and the operating pressure in the device.

The objective of this paper is to analyse the status of hydrogen infrastructure in KSA and highlight the energy sources in KSA, both conventional sources and renewable and clean sources through which hydrogen can be produced from. Our paper also conducts a simulation assessment for the use of PEMFC integrated with other renewable sources in NEOM city in the Kingdom.

2. PRODUCTION METHODS OF HYDROGEN

2.1 Non-sustainable methods

2.1.1 Coal

Coal is the most abundant fossil fuel on the earth, and it's estimated that around 23% of the world's energy comes from this source. Hydrogen can be produced via coal gasification, where oxygen or water steam is passed over coal at high temperature to yield mixture of gasses that includes hydrogen, and hence it can be separated after the process [4]. This process is a well-established technology that is most suitable for large-scale centralised hydrogen production.

Producing hydrogen from this resource has proven to be not as cost effective as producing hydrogen via other fossil fuels (oil and natural gas). Moreover, KSA has not been endowed with high coal reserves and hence coal has not been part of the energy mix in the country. This method therefore requires KSA to import coal, which is not economically ideal to improve the hydrogen infrastructure from in the country.

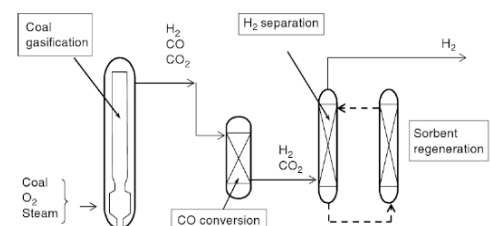


Figure 3: Process flow diagram of coal gasification

2.1.3 Natural gas

The World Energy Council estimates the natural gas reserves in KSA to be 8488.9 Billion cubic meters; this ranks the country the sixth globally for the proven natural gas reserves [5]. This source of energy has been used extensively throughout the past decades in the energy mix in the country, and accounted for around 41% of the country's energy consumption in year 2014. Natural gas in KSA is currently not being exported and is only used domestically to meet their growing energy consumption. However, the country is perusing to become a shale gas producer in 2020.

Hydrogen can be produced from natural gas through steam reforming. Globally, 48% of hydrogen production utilises this process, due to being more cost effective and having better overall efficiency as compared to other fossil fuels (between 65%-75%) [6]. Steam reforming is a two-step process through which methane from the natural gas is heated via steam in the presence of a catalyst to produce a mixture of CO, Hydrogen, and small traces of CO₂ (a molecule of methane yields 4 molecules of H₂). The major drawback of this process is the carbon dioxide emissions associated with the process, which will have an impact on environment. However this can be overcome through installing carbon capture and storage technology.

Presently there is only one purposely-built facility for hydrogen production in KSA, which is located on the red sea coast in the western region. This facility uses steam-reforming process and has the capacity to generate 400,000 Barrels per day of hydrogen. The hydrogen is currently being used in KSA only in refineries to reduce sulphur content of produced fuels. Furthermore, more recently there have been planned efforts and discussions between Japan and KSA to supply hydrogen in the form of ammonia produced through natural gas steam reforming with the deployment of CCS and the first commercial export of free-carbon ammonia to Japan is expected to be mid-2020 [7,8]. There is hence a great potential for increasing hydrogen production to support the growing demand and also the policy makers in KSA are acutely aware of utilising CCS technology to help in reducing the carbon footprint in the country. Table 1 shows the large-scale CCS projects for hydrogen production based (through steam-reforming) that were successfully launched [9].

Name of project	Country
AP Port Arthur Project	USA
Shell Quest Project	Canada
Tohokamai Project	Japan
AL Port Jerome Project	France

Table 1: Existing large-scale hydrogen plants projects that incorporate CCS technology

2.2 Sustainable and clean methods

One of the promising methods to produce hydrogen is through electrolysis of water. This method requires electrical energy through which renewable sources can be exploited. Additionally electrolysis technology offers better overall efficiency (80-85%) and has the advantage of being deployed in relatively smaller scales than the methods mentioned previously. Currently there are three main types of electrolyzers, Alkaline, PEM and solid oxide. These technologies are summarised in table 2.

Technology	Alkaline high pressure	Alkaline large-scale	Advanced Alkaline	PEM	Solid oxide
Status	Commercial	Commercial	Pre-commercial	Pre-commercial	Prototype
Operating temperature	70-90 °C	70-90 °C	80-140 °C	80-150 °C	900-1000 °C
Operating pressure (bar)	Up to 690 bar	1-25 bar	Up to 120 bar	Up to 400 bar	Up to 30 bar
Power requirement	56-60 kWh/kg	48-60 kWh/kg	42-48 kWh/kg	40-60 kWh/kg	28-39 kWh/kg

Table 2: Categories of electrolyzers and their specifications

Figures 4a and 4b shows the difference in the production cost and the pollutants social costs of renewable sources (via electrolysis) as compared to conventional sources [10].

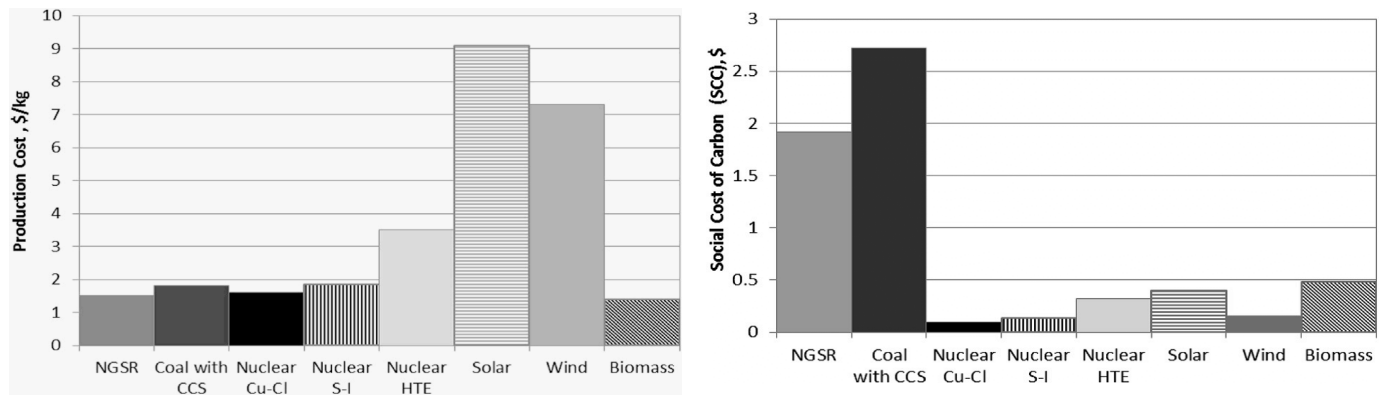


Figure 4 a) Production costs of hydrogen b) Social cost of hydrogen produced from different sources

As it can be clearly seen, hydrogen production through coal and natural gas are relatively lower than the other methods, however they are considerably more harmful and hence have higher pollutants social cost.

This section highlights the potential of the renewable sector in KSA in supporting the move towards hydrogen production through electrolysis.

2.2.1 Nuclear energy

Nuclear energy in KSA gained momentum in 2010 after the founding of King Abdullah City for Atomic and Renewable energy (KACARE). Two years after the founding of KACARE, it was announced that by 2032, out of the projected 132GWe electricity generation, 18GWe would be backed by nuclear power [11].

This resource of energy not only provides electricity but also heat, which can be used for high temperature electrolysis using solid oxide, which offers better characteristics compared to the other types such as high electricity to hydrogen efficiency and lower associated costs.

It has been reported that KSA is on the track of constructing 16 nuclear plants over the next 20 years, composed of small units for seawater desalination and large units for electricity generation [12]. This represents a significant opportunity for diversifying hydrogen production methods in the country, especially for those reactors located in the coast for desalination, in which electrolysis technology can be integrated onsite to take the advantage of the rich resource of water. Figure 5 shows a process flow of SMART (nuclear reactor type being constructed in KSA for desalination) integrating electrolysis technology to its operation [13].

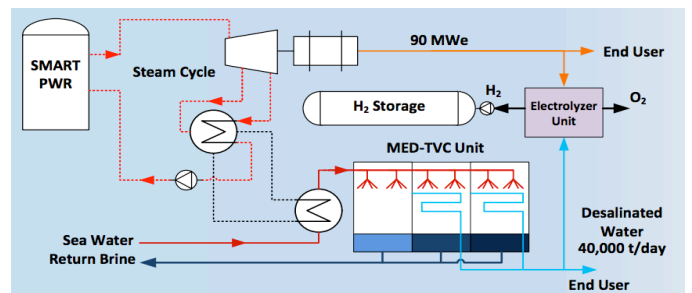


Figure 5: Process flow of hydrogen produced through SMART reactor

2.2.2 Solar energy

KSA has a huge potential of solar energy with an annual average daily global horizontal irradiance between 5700 Wh/m² to 6700 Wh/m² [14], which could essentially be exploited to generate electricity through photovoltaic cells for hydrogen production. Also due to the large area the country has, hydrogen production through solar energy can play a vital role in bridging the gap between the supply of fossil fuels and its export demand.

In 1986 KSA and Germany have started a research cooperation to investigate the feasibility of hydrogen produced from solar energy through the Hysolar Project. This has led to the installation of 350kW solar hydrogen production system, which became operational in 1993. The system utilises the electricity generated

by the PV cells to feed an advanced alkaline electrolyser and has a daily capacity to produce 463m³ of hydrogen [15]. After the implementation of this project the R&D team have made some remarks with regards to the technical challenges, with two main issues, the high associated cost of solar energy and the low conversion efficiency. Since 1993 the price of silicon PV cells have dropped exponentially to more than 90% of their price per power [16]. Therefore this effectively indicates that the cost of solar hydrogen have significantly reduced since the the project which increases the viability of hydrogen infrastructure in the country.

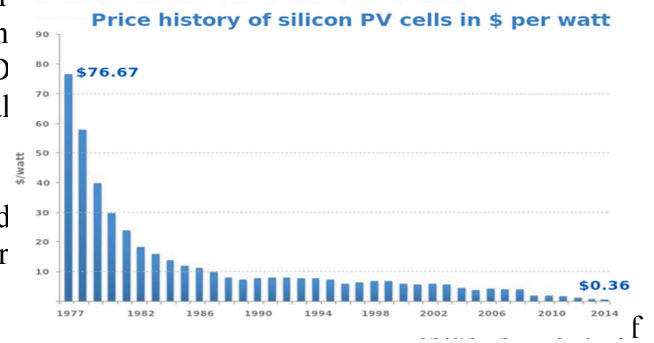


Figure 6: Price history of PV price [16]

In our study we examined the area needed for the PV system to supply 10% of the needed demand in KSA's electricity sector. By using two different values of the average annual growth rate (AAGR) of the country's consumption that was reported in 2015. Figure 7 illustrate the needed PV under two scenarios of AAGR. It can be clearly seen that small increase in the AAGR will significantly affect the required electricity needs in the country and hence solar hydrogen could play a vital role in the energy mix in the country in future. Also, the percentage of KSA's required area is less than 1% in both scenarios in year 2030, and hence the land required to produce hydrogen via solar energy is technically feasible even beyond 2030. Economically our results indicate that 75TWh and 49.5TWh of oil could potentially be saved under 7.1AAGR and 5.1AAGR scenarios respectively.

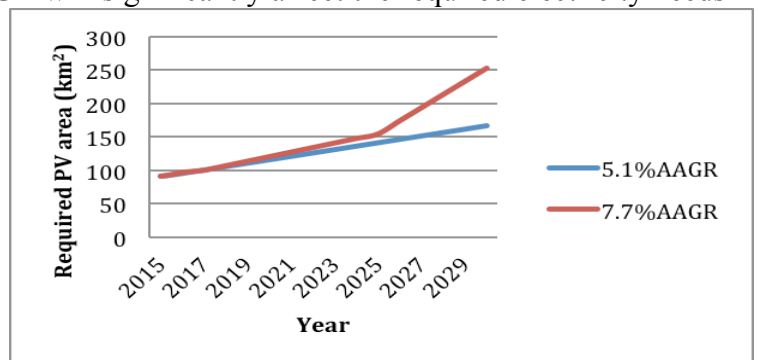


Figure 7: Required area of PV system to supply 10% of electricity demand

Beside PV solar cells, concentrated solar thermal power was reported to be a more viable option in the production of hydrogen mainly due the higher efficiency it provides [17]. Additionally, there are a number of emerging processes that harvest the solar thermal energy to produce hydrogen that can be exploited such as Hybrid sulphur cycle (two-step water splitting process). These technologies however are in the development phase due to the challenges it encounters in the materials side as well as the operational concepts in heat and mass flows.

2.2.3 Wind energy

Wind energy is another key renewable source that can be utilised in different regions in the country. It was observed that the northern region posses the best wind potential in the country, with average wind speed fluctuating between 3 to 7.3 m/s. Figure 8 shows the average wind speed for 6 different stations in the country's northern region which were recorded in 2015 [18].

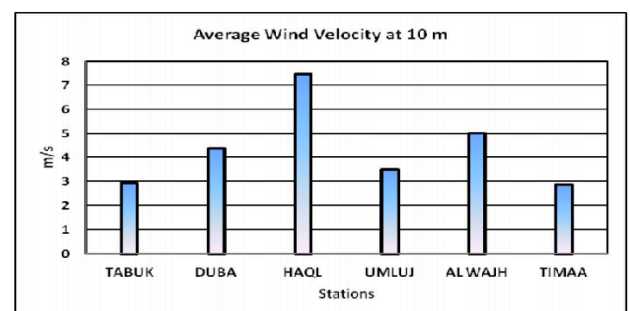


Figure 8: Average wind speeds in different areas in KSA

Recently, the Renewable Energy Project Development Office (REPDO) announced plans to construct a 400MW wind farm project in Midyan (northwest area) as a part of the first round of other energy projects [19]. This major step in deploying a new renewable energy source in KSA clearly demonstrates the potential of wind energy to partially fulfil the country's energy needs in future and subsequently help in reducing the social cost of carbon.

Hydrogen production through wind powered electrolyzers haven't been explored in KSA yet, however a number of researches were conducted to assess the feasibility of hydrogen production through wind energy in different regions around the world [20], [21] and [22]. This power source offers a significant investment opportunity to be implemented and developed in KSA for the consistency source of energy it provides and also for the fact that wind turbines contribute less carbon footprint over solar systems. Wind-powered electrolyzers are more convenient to be used in the least densely populated areas in the country due to the space it requires, which is accessibly available in many rural and coastal areas in the northern region.

2.2.4 Biomass energy

Since 1990, the population of KSA has increased almost 50%, and the country's agricultural and animal production as a result increased proportionally with this growth. It's estimated that the generation rate of municipal solid waste (MSW) in KSA is around 1.4kg per capita daily, and these wastes are mostly disposed in landfills after going through separation and recycling processes [23].

Production of hydrogen through biomass through biomass gasification has been intensively researched in the past few decades. This process converts the carbonaceous substrates into hydrogen at high temperatures between 800-900°C under controlled oxygen environment. This process however faces economic constraints due to the associated high capital and operational costs. However, the large-scale production of hydrogen via this process is promising and with the increase in demand for hydrogen as a fuel, this process could become feasible in the near future.

In 2014, the MSW was estimated to be around 15 million tones, which compromised 75% of organic waste. Figure 9 shows the compositions of the produced MSW in 2014 [24]. Besides, the agriculture waste is estimated to be more than 440 million tones annually with the majority of originates from date palm trees [25]. Furthermore, in KSA's industrial sector there are more than 12 thousand plants that generate significant amounts of waste in a daily basis and is projected to be between 1.6-1.8 thousands dry tones per day in mid-2020s [26]. Presently there are no exiting waste-to-energy facilities and hence this source of energy can potentially be utilised in the production of hydrogen in the country.

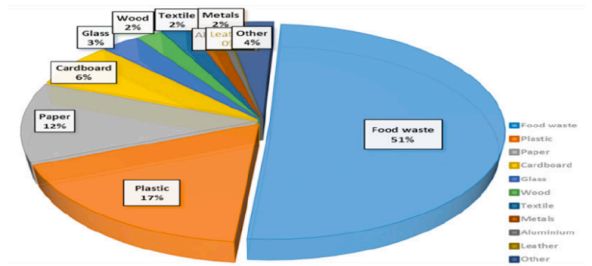


Figure 9: MSW compositions in KSA in 2015

3. ECONOMIC ASPECT OF HYDROGEN PRODUCTION

Although more sources for hydrogen production exist (figure 11 [27]), the previous section in this paper only highlighted the predominantly potentials of sources that exist in KSA. From an economical prospective, two main constraints are critical when choosing the source of production, the efficiency of the process and the production cost of H_2 .

Currently, the cheapest method for hydrogen production is through steam reforming of natural gas. The cost of production of H_2 through this process is reported to be about \$7/GJ (without CCS) [28]. Water electrolysis has high efficiency and is one of the simplest technologies exist to produce H_2 . The cost of H_2 production through this process highly depends on the cost of the input electricity, which represents 77% of the overall cost of the system [29]. Moreover the cost of biomass gasification to produce H_2 is between 10-14\$/GJ, which is almost two times greater than the cost obtained steam reforming [30].

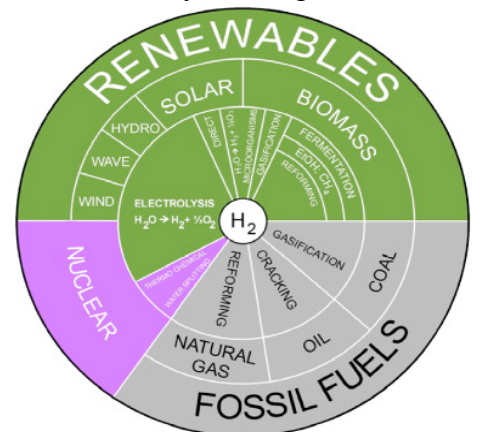


Figure 11: Classifications of Hydrogen production routes

In KSA hydrogen production can be produced through steam reforming combined with CCS in different regions in the country to help in establishing the hydrogen infrastructure in the country. Hydrogen gas can be transported using the same pipelines that exist for the transportation of natural gas, and more pipelines can be constructed as the demand for this fuel grows. The recent institutional reforms in the country have resulted in the partially lifting of governmental subsidies (which included electricity price) and this is expected to continue for the next decade. Besides, costs of renewable energy technologies are projected to further reduce, and the viability of hydrogen production through renewables is consequently expected to compete with conventional methods in the long term.

3. APPLICATIONS OF HYDROGEN ENERGY IN KSA

4.1 Electricity production

The primary energy mix in KSA for electricity is heavily based on oil and natural gas only. The energy consumption in the country has been growing at a faster rate than the GDP mainly due to governmental subsidies in electricity tariffs. The electricity demand in the residential sector remains solid as it accounts for the consumption of 50% of the total electricity production in the country, and around 70% of electricity sold goes to air conditioning [31]. In light of these facts, the country strongly needs to diversify its energy sources by the deployment of renewables in order to sustain in the long run, in which hydrogen energy could play a part.

In our study we investigated the integration of a 4kW PEMFC and an electrolyser to produce hydrogen onsite to a house in KSA, located in Haqal (which will be part of NEOM project). The electricity load data were sourced from a study conducted in Algeria for a house exposed to the same weather conditions [32]. In our model we assume that no grids are connected and the house runs 100% on renewable energy sources (PV solar and wind turbine). Figure 12 shows the process diagram of the model, which was simulated in Homer software. The results of our simulation showed that integrating PEMFC and Electrolyser systems would reduce the operating costs by 18% and also reduce shortage capacity by 4%. Furthermore the annual production of hydrogen by the electrolyser is 111 kg, with a daily production ranging between 0.16 to 0.39kg. Figure 13 shows the monthly average hydrogen production of the electrolyser. Also figure 14 illustrate the electric production by source, where the PEMFC contributed 6% to the overall production.

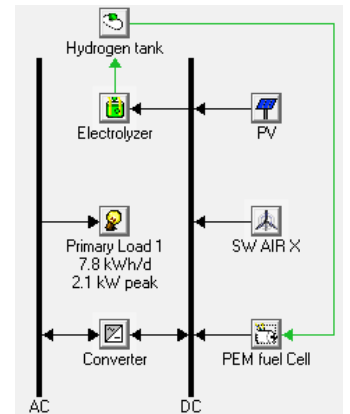


Figure 12: Flow diagram of the model

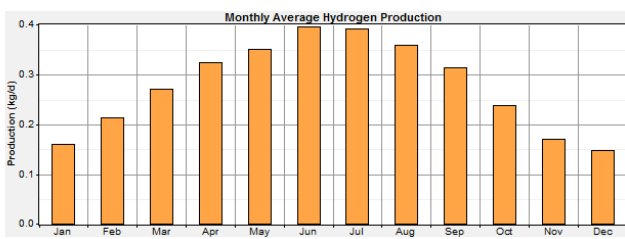


Figure 13: Monthly production of hydrogen by electrolyser

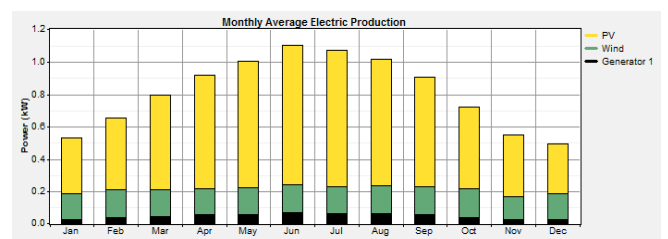


Figure 14: Electric production by source

This investigation clearly shows the advantageous of introducing a PEMFC system to the house, as hydrogen can be converted into electricity, especially when the tariffs are higher. Besides, the heat generated by the PEMFC stack can potentially be utilised (via heat exchangers) to provide heating needs to the household.

4.2 Transportation

As of 2015, the number of active vehicles in KSA was estimated to be over 12 million [33]. These vehicles consume almost 811 thousands of oil barrels on a daily basis. The current pace of growth in the country indicates that by 2030 the number of vehicles is expected to reach 26 million. The carbon dioxide emissions

contributed by the transport sector in the country was around 55 million metric tonnes (based on average emissions per car [34]) in 2015 and the emissions are expected to double by 2030 if the business as usual scenario is unchanged.

PEMFC can potentially be adopted in the transportation sector due to the associated environmental and economical benefits it delivers. In fact a number of automakers have already introduced fuel cell powered vehicles versions to their fleets, including Toyota and Honda [35]. Some governments have also started to invest in PEMFC technology to be part of their public transport system. Also Tabbi [36] have extensively reviewed the current advances in PEMFC powered vehicles and future projections.

In this study we presented a scenario where PEMFC is gradually introduced in the KSA's transportation sector in 2020 to completely replace existing internal combustion vehicles (ICVs) in 20 years period. Figure 15 shows the proposed number of vehicles (PEMFCVs and ICVs) versus time. Our analysis indicate with the introduction of this scenario over 1300 million metric tonnes of carbon dioxide emissions will be avoided by the beginning of year 2040. Additionally, the total economical savings of fossil fuels if this scenario is introduced would be more than $5 \cdot 10^{11}$ litres in the 20 years period.

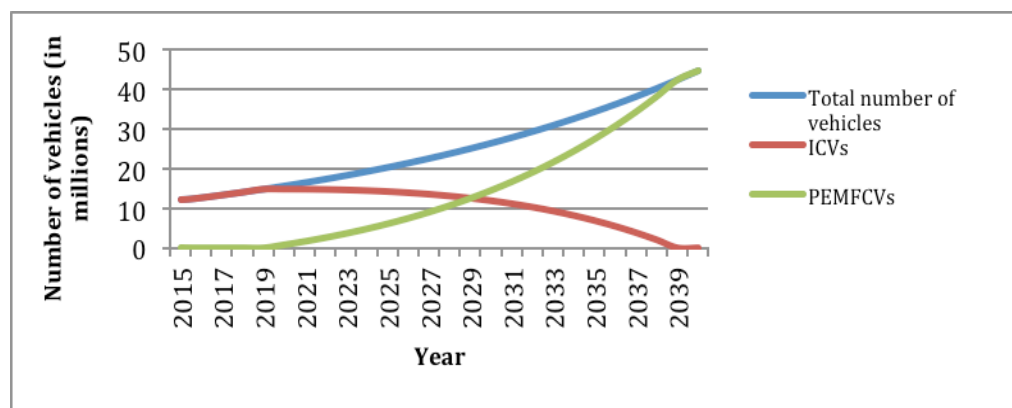


Figure 15: Number of vehicles vs time

4. CONCLUSION

In this study, the potential of achieving sustainable development in KSA through hydrogen energy was demonstrated. The study highlighted the country's energy sources, both conventional and sustainable, which possesses for hydrogen production their costs were compared. In addition, the report proposed the utilisation of PEMFC in two main sectors electricity generation and transportation sectors and the associated economical and environmental benefits were highlighted.

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